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# *Balloon Tracking for the ASTEX/MAGE Lagrangian Experiment: 1994 Technical Report for ONR project : N00014-92-J-1285*

*by*

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April 1994

## *1. Executive Summary*

The Lagrangian experiments in Atlantic Stratocumulus Transition Experiment/Marine Aerosol Gas Exchange (ASTEX/MAGE) were the first attempt to repeatedly sample the same remote marine air parcel over an extended period (36 to 48 hours), permitting observation of chemical changes in the sulfur budget (in particular, the formation of sulfate aerosol from biogenic DMS gas) while limiting the complication of advection through the sampling area.

Our goal in supporting the Lagrangian experiments is to provide tetroon location data and analysis of relevant meteorological data to provide: a) an unambiguous track of a chosen volume of air, b) estimate the entrainment through the MBL inversion, and c) estimate the impact of air-mass divergence.

## *2. Current Research*

The initial goal to provide tetroon location data and analysis of relevant meteorological data to provide an unambiguous track of a chosen volume of air was completed during 1992 and reported in the 1993 Annual Technical Report submitted to Ed Green in March of 1993. Three research efforts and related papers are currently being prepared under this project. These include:

i) Effort to develop a "smart" balloon that will be deployed in follow on Lagrangian experiments during the Aerosol Characterization Experiment (ACE-1) to be held in Tasmania during November and December 1995.

ii) Modeling effort to investigate the evolution of the Marine boundary layer during the ASTEX Lagrangian experiments.

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iii) An investigation of the veracity of using tetroons to track air parcel motion, leading the the composing of a review paper entitled "Tetroons as a Measurement Platform for Atmospheric Research."

### *3. ACE-1 and the Development of an Isentrope-Following Balloon Facility*

A new field project, the Atmospheric Chemistry Experiment (ACE-1) is being developed under the leadership of Dr. Barry Huebert to take place in the relatively clean atmospheric environment of the Southern Hemisphere. During the period 15 November to 15 December 1995, under favorable westerly flow conditions, balloons will be launched from ship board at a location to the south of Perth, Australia, and will be tracked eastward to Tasmania and New Zealand. The clean atmosphere characteristic of the Southern Hemisphere will make the execution of Lagrangian experiments easier, permitting observation of chemical changes in the sulfur budget (in particular, the formation of sulfate aerosol from biogenic DMS gas) while limiting the complication of varied air masses moving through the sampling area, as was the case in the second MAGE Lagrangian. The non-homogeneous air mass in terms of pollution and aerosol concentrations encountered during the second MAGE Lagrangian, though interesting for other reasons, make the chemistry budget calculations more difficult to interpret.

In particular the smart balloons would be deployed during the Atmospheric Chemistry Experiment (ACE-1) Lagrangian experiments to be directed from Tasmania, Australia from 15 January to 15 March 1995 for the purpose of tagging the air mass in which a number of data collecting platforms will be focusing on atmospheric chemistry and boundary layer experiments. The ACE Lagrangian experiments are designed to monitor changes in the sulfur budget in a truly remote marine boundary layer (MBL) over at least a day, providing estimates of sources, sinks, entrainment, and conversion rates for sulfur gases and aerosols.

Constant density tetroons deployed during MAGE were adversely affected by precipitation, which caused the balloons to fall due to water loading. To overcome this serious deficiency in balloon design, we are proposing to develop "smart, isentrope-following" balloons. In addition to providing track information as their predecessors did, these balloons will carry pressure, temperature and humidity sensors. These data will be transmitted along with the GPS derived position data. By including pressure and temperature sensors and a pressure pump, the balloon can be programmed to track along an isentropic surface. The blasting of the balloon will be achieved using an expandable balloon inside a pressurized balloon (an existing technology). The strength of this capability is that neglecting diabatic influences (radiation, latent heating) air parcels follow isentropic surfaces. The balloons, therefore, can provide a better approximation of the movement of the air during a Lagrangian experiment. The ability to control the balloons height offers the additional possibility of preforming soundings during flight, a capability that

could prove powerful in mesoscale dynamics experiments. These balloons would then comprise a "facility" for the atmospheric sciences research community to deploy during field experiments with a variety of goals ranging from storm structure to atmospheric chemistry problems.

Dr. Ray Dickson and Mr. Randy Johnson of the NOAA Environmental Laboratory ARLFRD at Idaho Falls, who perfected the GPS tracking system on 1 $m^3$ tetroons used during ASTEX/MAGE, will bring their significant expertise in balloon development and launching to the project.

### *4. Isentrope Following Balloon: Design and Development*

The design goal for this project is to develop a "smart" tetroon and Global Positioning System (GPS) transponder package that builds on our prior GPS tetroon tracking experience and adds new monitoring and control features (Fig. 2). The previous GPS transponder design provided 3 days of operation and transmitted position and altitude data from each transponder every 5 minutes. The new GPS transponder design will add sensors and controls that provide altitude monitoring and control. The addition of altitude control will allow tracking at a constant altitude or constant potential temperature as well as compensation for reasonable changes in tetroon lift due to precipitation or other external influences.

The design and development of the "smart" tetroon will be achieved in coordination with Dr. Ray Dickson, Mr. Randy Johnson and Mr. Roger Carter of the NOAA Environmental Laboratory ARLFRD at Idaho Falls. Dr. Dickson and Mr. Randy Johnson perfected the GPS tracking system on 1 $m^3$ tetroons used during ASTEX/MAGE, and will bring their significant expertise in tetroon development and launching to the project (Please see attached letter of intent from Mr. Johnson).

*The Smart Tetroon will have the following functions/components (Fig. 3):*

A. Barometric pressure transducer - this will be used by the micro controller to measure altitude without the variation in height or power consumption that is experienced with the GPS receiver.

B. Gage pressure - gage pressure is necessary to measure the pressure of the outer rigid super-pressure tetroon. Data from this will allow the micro controller to take the correct control action to maintain altitude.

C. Ballast and ballast control hardware and software.

D. Pump, Pump Drive Hardware, and pump control software.

E. Pressure relief valve for both the outer tetroon and the inner balloon.

F. Temperature/relative humidity transducer - this is used to relay temperature/relative humidity information along the flight path and for altitude/isentropic surface control calculations.

G. Use an expandable balloon within a pressurized tetroon. These are already developed and have been used in the past.

### *4.1 Tetroon Design Principle*

A tetroon and payload will obey Archimedes' Principal: A body immersed in a fluid is buoyed up by a force equal to the weight of the fluid displaced. A tetroon and payload will rise when the total amount of air displaced is heavier than the tetroon and payload. When the total weight is equal to the displaced air the tetroon will have zero lift and maintain altitude.

A tracer tetroon should move into the desired parcel of air at a predetermined altitude or potential temperature. Our goal is to design a tetroon that will rise as quickly as possible from the release point to the altitude of the desired parcel of air and stay in that parcel of air throughout the experiment.

A constant volume tetroon has a unique feature. It reaches equilibrium at only one density level in the atmosphere. For this reason, a constant volume tetroon works fairly well for tracking a parcel of air. However, there are several factors that influence a constant volume tetroon's altitude. These are:

1. Precipitation or condensation collecting on the exterior of the tetroon cause the tetroon weight to increase and the tetroon loses altitude.
2. Leaks in a constant volume tetroon initially cause the tetroon to gain some altitude then lose altitude.
3. Stretching or shrinking of the tetroon material because of pressure changes or changes in temperature cause the tetroon to gain or lose altitude.

Any of the above factors can cause the tetroon to move out of the parcel of air being tracked in an experiment. Therefore, it is desirable to keep the self regulating altitude characteristic of the constant volume tetroon and allow for lift adjustment during an experiment as required.

### *4.2 Constant Volume, Variable Lift Tetroon*

The proposed tetroon design provides the self regulating properties of the constant volume tetroon while allowing for altitude adjustment. This design is achieved by inserting a zero pressure helium filled balloon inside a constant volume tetroon filled with air (see Fig. 2). At the beginning of an experiment the tetroon is ballasted for the desired air density level. If a higher altitude is required during the experiment, air is released from the pressurized constant volume tetroon. This allows the helium filled balloon inside to expand to take the place of the heavier air that is released. The density of the tetroon decreases while the volume stays the same and the tetroon moves to a higher altitude. If a lower altitude is required, outside air is pumped into the

pressurized constant volume tetroon which increases the density of the tetroon causing it to move to a lower altitude. In combination with potential temperature determination from sensor data, the balloon can be programmed to follow an isentropic surface or constant pressure surface, whichever will most closely approximate a trajectory of air parcels.

### *4.3 GPS Transponder and Altitude Control Considerations*

The factors that must be taken into consideration in the design of an adjustable altitude tetroon with GPS transponder and control package include such items as:

1. Tracking time
2. Tracking range
3. Altitude window of operation
4. Payload weight
5. Number of temperature cycles that will be encountered
6. Amount of battery power available
7. Possible rain or condensation on the tetroon

Our goal is to design a tetroon and transponder package that will allow for a reasonable number unforeseen problems, compensate for these and provide valuable information on the air parcel being tracked during an experiment. Our design goals include but are not limited to the following capabilities:

1. Tracking time of 3 days
2. Barometric pressure measurement
3. Temperature measurement
4. Relative humidity measurement
5. Interactive field configuration capability
6. Data transmission radius of greater than 100 miles
7. Transponder weight of less than 1 pound without batteries
8. Ability to track 30 or more transponders at one time
9. Transponder cost at less than $2,500 each

To provide better data and account for environmental variables that may be encountered during the course of a tetroon experiment, the following measurement and control capabilities will be designed into the earlier transponder package.

*1. Barometric Pressure.*

Once every 5 minutes the GPS will output ±100 meter altitude data. However, to provide better accuracy at a much lower power supply current drain, a barometric pressure transducer will be designed into the transponder package. The barometric pressure will be used to calculate

the tetroon altitude, altitude changes and rate of altitude change. A barometric pressure gage can be measured every few seconds at a small fraction of the power required by the GPS receiver and be capable of measuring altitude changes of ±3 meters.

*2. Temperature*

Temperature data will provide important thermodynamic information to the experiment, and will be used as an input to the algorithm that calculates tetroon lift. The transponder altitude control algorithm will take temperature and pressure into account when determining if adjustments to lift are necessary. With the combination of temperature and pressure data available, potential temperature can be calculated and used as a constant for the tetroon to track.

*3. Relative Humidity*

Relative humidity will provide valuable information on moisture content in the air and will be transmitted back and saved as experiment observational data along with the other sensor and GPS data. Relative humidity data will also provide an input to the controller that can be used to indicate the possibility of rain or condensation collecting on the tetroon. Checking for relative humidity at or near 100% during times of altitude loss will help the control system determine if altitude loss is being caused by precipitation or condensation rather than a turbulent or convective down draft. In future, constant equivalent potential temperature can be computed and tracked in studies involving moist processes.

### *5. Numercial Simulation Experiments of the Marine Boundary Layer During the Astex Lagrangian Experiments*

In August of 1993 Elisabeth Wolf, an MS student funded by the project abruptly quit the program at NCSU after getting married. She was in the final stages of an analysis and modeling study of the marine boundary layer during the two Lagrangian experiments. An abstract based on this work is given below:

**Marine Stratocumulus Convection in the ASTEX Region: A Comparison of Model Results and Observations**

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Department of Marine, Earth and Atmospheric Sciences
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Raleigh, North Carolina 27695 - 8208

On 12 - 14 June 1992 the first of two Lagrangian experiments was conducted, in an attempt to repeatedly sample the same remote marine air parcel over an extended period of time. Instrumented aircraft followed six constant level tetroons for eight hours and monitored the growth of the marine boundary layer in the ASTEX region. Observations from the period indicate that the marine boundary layer evolved from a shallow boundary layer with moderate precipitation at the northern edge of the triangle on 12 June 1992 to a deep boundary layer with

strong winds and light drizzle at the southern edge of the region on 14 June 1992. This boundary layer structure appears to respond to an observed increase in sea surface temperature.

A two dimensional numerical model is used to simulate atmospheric conditions of 12 June 1992 in the ASTEX region. The model uses turbulent kinetic energy (TKE) and dissipation equations to define turbulence closure. This, combined with the level 2.5 scheme developed by Mellor and Yamada (1982), provides a simple and accurate estimation of the eddy Prandtl number.

Preliminary model results indicate a good correlation between actual observations and model output. Further analysis and simulations will provide additional insight into the evolution of marine stratus as it passes over increasingly warm ocean surface.

Ms. Wolf's abrupt departure created a delay in this analysis and modeling research effort. Steven Chiswell has taken over this work and we expect results within the next six months.

***6. An Investigation Of The Veracity Of Using Tetroons To Track Air Parcel Motion, Leading The The Composing Of A Review Paper Entitled "Tetroons As A Measurement Platform For Atmospheric Research."***

A draft of this manuscript follows.

# *Tetroons as a Measurement Platform for Atmospheric Research*

by

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To be submitted to the ***Journal of Geophysical Research***

*Draft* April 1994

## 1 Introduction

Balloons have provided a dedicated meteorological instrument platform since the early 1800s (Ley 1911). The meteorological application of balloons has had a colorful history from manned balloons that first carried thermometers (1784), the first pibal at Blue Hill (1909), to constant level balloons (CLB) flown by the Japanese during WWII with bombs attached. This article will focus on balloons designed for controlled flight. Although stratospheric constant volume balloons (CVB) are mentioned in this review, emphasis will be placed on lower tropospheric balloons. The use of tethered balloons, rawinsondes, and other free-flight balloons to investigate meteorological problems will be left to the reader.

Early CLBs were crude devices that more or less followed constant pressure surfaces (Angell 1961). As materials for balloon fabrics progressed, the superpressure constant volume balloon was developed. Both CLBs and CVBs were initially flown at upper tropospheric levels.

The "tetroon" was first flown in the late 1950s as a lower tropospheric CVB platform that was monitored by radar and transceivers and did not carry meteorological sensors (Angell and Pack 1960). Balloon systems monitored through electronic means are referred to as transosondes. The term tetroon is derived from a combination of "tetrahedral", its shape, and "balloon." In its current usage the term tetroon has been applied to spherically and cylindrically shaped balloons, leading to possible ambiguity. In the literature, tetroons are usually relegated to the PBL, whereas CLBs are used in the upper troposphere and above.

## 2 Balloon fundamentals

A key to the CLB's success was use of new materials and instrumentation. Polyethylene

balloons of 2-2.5 mil limitations were used. This material was found to be flexible to about -80°C, show high resistance to ozone or UV degradation, and have low permeability. Furthermore, polyethylene has high strength, high tear resistance, and small radiation absorption.

The use of Mylar® fabric, which has all of the desirable characteristics of polyurethane plus additional strength, has been used by superpressure CVBs. Unfortunately, the mass of the instrument package is a much larger percentage of the total mass of the system and subsequently must be made as light as possible. A fundamental drawback to any balloon system is the limitation set forth by the FAA which constrains the total system to 6 lb. (2.7 kg) over U. S. territories. Therefore, the associated instrument packages must be miniaturized. As will be shown later in the paper, with the advent of modern electronics, the weight of the instrument package is not a hindrance.

Before the low permeable Mylar® fabric was developed, the limitation to long distanced tetroon flights was the loss of gas. The other problem that needed to be addressed was the diurnal expansion and contraction of the balloon envelope due to radiational heating which caused the tetroon fluctuate in altitude. The superpressure constant volume balloon (CVB) was developed to address these problems Angell (1961). The advantage of the superpressure CVB is determined from the following equation.

$$W_s = V_b(\rho_a - \rho_h) \qquad (1)$$

Where $W_a$ is the weight of the system (including lift), $V_b$ is the volume of the balloon, $\rho_a$ and $\rho_b$ are densities of the ambient air and helium, respectively. Since the buoyancy of the system is not adversely affected by the total mass of helium, an excess amount of helium can be added to the balloon so that leakage or decrease of temperature of helium will not require the use of a ballast system. The use of added helium to the balloon gives the superpressure name for the system.

### *Flight Physics*

The basic premise of the tetroon system is the ability to float an instrument package at a given elevation or pressure surface within a moving or stationary air parcel. The equilibrium level of a tetroon system (balloon and instruments) is determined by multiplying the volume of the balloon by the difference in ambient air and helium. To achieve balance in the atmosphere many forces are in play and these forces are always seeking balance. From a simplistic standpoint, gain of eddy kinetic energy (due to Reynolds stresses), loss of kinetic energy (due to viscous dissipation), buoyancy forces (changes in lapse rates), flux divergence, and work against gravity must be must be taken into account for a complete understanding of tetroon motion.

A more complete equation for the balance of the tetroon system and subsequent vertical motion is given by Nastrom (1980) as:

$$(M_B + \eta M_a)\frac{\partial^2 z}{\partial t^2} = (M_a + \eta M_a)\frac{\partial w_a}{\partial t} - 1/2\rho_a C_d A_B\left(\frac{\partial z}{\partial t} - w_a\right)\left|\frac{\partial z}{\partial t} - w_a\right| - g(M_B \pm M_a) \qquad (2)$$

where

| | |
|---|---|
| $M_B$ | mass of the balloon system (skin + gas + instruments) |
| $M_a$ | mass of the displaced air (i.e. equal to $\rho V$ ) |
| $V$ | volume of the balloon |
| $z$ | displacement of the balloon from its float level |
| $A_B$ | cross sectional area of the balloon |
| $C_D$ | form drag coefficient |
| $\eta$ | added mass coefficient |

The terms on the right-hand side of (2) are the dynamic, form drag, and buoyancy terms respectively.

The theorem for which tetroon flight is based is quite simple. Archimedes' Principal states that a body immersed in a fluid will be buoyed by a force equal to the weight of the fluid displaced. A displaced tetroon system will cease movement when the total weight of the air displaced is equal to the weight of the tetroon system. More importantly, a tetroon will only float at one density level in the atmosphere. A complete treatise on tetroon flight preparation and limitations can be found in Lally (1967) and Tatom and King (1977).

### *Aerodynamics And Vertical Air Speed*

Hoecker (1975) used superpressure tetroons as a first rate estimate to determine vertical air speed. It was found that in convective conditions the balloon will float at a slightly higher equilibrium condition because the upper boundary is unlimited, versus the earth restricting both parcels and balloons. However, Mylar® balloons showed "creep" where the tetroon skin stretched slightly during ascent and hysteresis effects were noted where the balloon returned to lower levels. Hoecker (1975) speculated that hysteresis effects could be minimized by keeping superpressure at reasonable levels and using smaller tetroons.

The question of the ability of the tetroon to depict true vertical air motion was addressed by Hoecker (1973). Angell (1964b) noted that tetroons probably under represented vertical motions by at least 25% because of restoring forces acting on the balloon. The vertical air speed is composed of the sum of the tetroon relative vertical air speed and the air vertical speed. However, the tetroon's vertical displacement is due to the displacement from the equilibrium float level. For a tetroon to mimic a fluid particle, the tetroon must present a suitable profile to

the wind. For a Reynold's number to be calculated a tetroon drag coefficient must be determined Whannel (1965) and Hoecker (1973). Typical drag coefficients of 0.7 - 0.8 were found for 105 cm and 150 cm Mylar® balloons of 0.05 - 0.1 mm thickness for various air speeds (Cherry, 1971), and (Hoecker, 1973). The nearly uniform value of 0.7 - 0.8 for the drag coefficient is important if tetroons motion is to show consistency from one flight to the next.

### *Reynolds Stresses*

Atmospheric forces can manifest itself in many unusual forms that were empirically discovered by tetroons such as loops (cyclonic and anticyclonic) Angell, et al. (1972), and longitudinal roll vortices (helices) by Angell, et al. (1968) and Angell (1972). These vortices from large transverse circulations at the time were thought to be efficient carries of downward momentum.

Angell (1964b) and Dickson and Angell (1968) used tetroons to investigate 3D kinematics and dynamics of the boundary layer. Eddy kinetic energy (equivalent to vertical flux of momentum) can be determined from zonal Reynolds stresses. The governing equation can be expressed as:

$$\tau_x = \overline{\rho u'w'} \tag{3}$$

Where $\rho$ is density, $u$ and $w$ denotes horizontal and vertical velocities, and primes indicate deviation from the mean for each tetroon flight. It was found by Angell (1964b) that derived wind stresses are on the order of 0.5-2 dyne/cm$^2$ which corroborates the nominally accepted value of 1 dyne/cm$^2$. It should be noted that Reynolds stress varies directly as lapse rate increases (decreases), and varies throughout the PBL.

Likewise the production of eddy kinetic energy (Reynolds stresses) can be derived from:

$$\dot{K}_R = -\overline{V'w'}\frac{\partial V}{\partial z} \tag{4}$$

Where $V$ is wind speed, $w$ is vertical velocity, and $z$ is altitude. Unfortunately for (4) to work, the vertical wind shear must be known. Angell (1961) showed that the inertial oscillation of the tetroon is apparent in areas of vertical geostrophic wind shear, and Angell (1964b) noted that tetroons tend to underestimate vertical wind shear.

However, an approximation for the vertical wind shear could made Angell, et al. (1968) with tetroons. This approximation is made by averaging the longitudinal and lateral wind speeds for those times when the tetroon was above and below and mean flight level, and then dividing the by the approximate height interval. With the advent use of aircraft used in recent tetroon experiments, the ambiguity of vertical shear could be calculated more precisely than with tetroons.

### *Oscillations*

Wave theory has become in integral part of dynamic meteorology with large scale motions and micro-scale turbulent theory being dependent on the understanding of theses oscillations. Use of aircraft and soundings have traditionally used been used to determine atmospheric oscillations. However, only the tetroon allows the measurement to be averaged over any time interval which could interrogate the oscillation desired.

Of prime importance to tetroon flights is the ability for a tetroon to follow the actual air trajectory of a parcel. Hirsch and Booker (1966) and Reynolds (1973) found that for sinusoidal trajectories of air parcels, the tetroons tended to react faster and have less amplitude that the actual air mass. Except for inertia effects, change in air densities, and convective events, the actual tetroon streamline amplitude can be easily corrected.

Once a tetroon establishes its equilibrium level or equilibrium density surface (EDS), the balloon does not usually stay at equilibrium level for long. Instability is caused by the balloon's neutral buoyancy oscillation (NBO), gravity waves, and turbulence. NBO is a free mode oscillation about equilibrium, whereas gravity waves or turbulence is not free mode, but can take place at near equilibrium levels. Time variation in the balloons EDS more strongly influences balloon motion than vertical wind speeds.

From the simplest standpoint, the Bunt-Väisälä period as determined by Brunt (1927) and noted by Angell (1964a) and other investigators as the natural period of oscillation as:

$$P = 2\pi\left[\frac{T}{g(\gamma_p - \gamma)}\right]^{1/2} \tag{4}$$

where: $T$ is absolute temperature, $g$ is gravity, $\gamma_p$ is process (dry) lapse rate, and $\gamma$ is ambient lapse rate. On daytime flights, oscillations of 20-30 minutes indicating a Brunt-Väisälä period which corroborated the daytime convective regimes found by Angell, et al. (1969).

Massman (1978) also found that NBO frequency is a function of time in dampening. This dampening is a result of wind shear, viscous drag, and aerodynamic drag. Not only does the balloon respond to oscillations in vertical wind speed, but the balloon will also respond when its EDS is in motion. Hanna and Hoecker (1971) and Massman (1978) used perturbation methods with a "smallness" parameter $0$ , while neglecting resonance solutions.

Using: $$\varepsilon = \frac{\omega^2 \zeta \Delta Z}{\omega N^2} \tag{5}$$

With: $\zeta = \frac{1}{3}\rho_a A_b C_d / M_b$ and $\kappa = (\Gamma_d - \gamma)/(\Gamma_a - \gamma)$

Where:

| | |
|---|---|
| $\omega$ | atmospheric driving force |
| $\omega N$ | NBO frequency |
| $Z_a$ | height of the potential temperature surface |
| $N^2$ | Brunt-Väisälä frequency |
| $\rho_a$ | density of air displaced by the balloon |
| $A_b$ | cross-sectional area of the balloon |
| $C_d$ | drag coefficient |
| $M_b$ | mass of the balloon system |
| $\Gamma_d$ | dry adiabatic lapse rate |
| $\Gamma_a$ | 34.2 °C km-1 |
| $\gamma$ | environmental lapse rate |

The first approximation of the amplitude of the balloon's EDS is:

$$\left[Z_0(t)-\overline{Z_0}\right]=\left(\frac{\Gamma_d-\gamma}{\Gamma_a-\gamma}\right)\left[Z_a(t)-\overline{Z_0}\right] \tag{6}$$

Where:

| | |
|---|---|
| $Z_0(t)$ | time-dependent height of the balloon's EDS |
| $Z_a(t)$ | time-dependent height of the potential temperature surface |
| $\overline{Z}_0$ | some constant height about which the oscillations take place |

After neglecting drag force and other minor terms, ( ) can be simplified as:

$$\left[Z_0(t)-\overline{Z_0}\right]=\kappa\Delta Z_a\cos(\omega t)+1/2\sin\left(\frac{dZ_b}{dt}-w\right)(1-\kappa)^2\in\Delta Z_a\left(\cos(\omega t)-1\right) \tag{7}$$

The solution just given is valid if $\kappa >> \in$ and therefore the balloon will follow its EDS Massman (1978) and deviations from the EDS will be small. Therefore, when balloon oscillations occur with $\kappa >> \in$, the oscillation is not due to vertical wind, but rather is generated from the balloon's EDS. Under this scenario, the balloon is a true isopycnic tracer. Reynolds (1973) found that in the Mountain Wave Project the superpressure balloon responded well as a isentropic and isopycnic tracer.

Nastrom (1980) found for a typical gravity wave, the balloons' amplitude is linearly affected by vertical air motion, and nearly shows a one-for-one response to various lapse rates. Later Nastrom and VanZandt (1982) showed that in a vertically propagating gravity wave of short period and wavelength, may at times simultaneously encounter both vertical shear and pressure. For this scenario the balloon may oscillate at a frequency between sloshing $(\partial U / \partial t \neq 0)$ and shearing $((\partial U / \partial z \neq 0))$. For long period gravity waves the balloon is nearly

a true isopycnic tracer for high static stability but not so under low static stability conditions. As long as constant density balloons measure temperature, pressure, and height, the necessary corrections can be made.

An important consideration in determination of atmospheric oscillation is locality. In the lower troposphere the tetroon will oscillate near its' "natural" period of 10 min. (approximately the NBO frequency) whereas at higher altitudes (i.e. above the PBL) the tetroon will come under the influence of gravity waves (Angell and Pack , 1962). It was also noted by Angell and Pack (1962) that Lagrangian transverse values and turbulence at 3 000 ft over the ocean are an order of magnitude smaller than Eulerian values near the ground. Possible implications are that low level tetroon flights are easily grounded. Studies in desert terrain by Angell and Pack (1961) showed a net downward momentum transfer which could possibly trap the tetroon at ground level.

For the upper troposphere and stratosphere Massman (1978) found that NBO should have a period of about 3 to 4 minutes in the tropics. Whereas, in mid-latitudes the NBO period was in the 4 to 5 minute range. In the stratosphere the Bunt-Väisälä oscillations with a 5 minute period can compete with stationary lee waves with periods between 6 and 10 minutes which are generated by mountains. Therefore, the mid-latitude stratospheric NBO period tends to be longer than the tropical stratospheric period.

As a limitation to tetroon flights, Angell, et al. (1972) and Hoecker (1975) found that the tetroon responded well to large vertical air motions as long as the period of oscillation is relatively short. However, it should be emphasized though that in many instances tetroon motion is straight-forward and complications (e.g. unusual oscillations, etc.) do not arise.

*Experimental Conditions*

Tetroon flights do not exactly follow vertical air motions precisely, but tetroon flight data can be corrected through analytical means or tetroon networks. From earlier experiments by Durst and Gilbert (1950) and Angell (1958); Angell, et al. (1977) used paired tetroons to determine if tetroon trajectories are actually indicative of atmospheric motion. It was shown that there was consistency between tetroon pairs, and differences in vertical air motions were attributed to spacing of the tetroon pairs which were separated by one minute intervals.

Although an investigator may use a single tetroon for an experiment, most likely multiple tetroons will be utilized. Possible scenarios are that several tetroons can be launched at the same, or tetroons can be launched at set intervals. Pack and Angell (1963) noted that for dual tetroon release during the first 100 min. of release the horizontal separation distance was approximately equal to the third power of time and that after this time tetroons tend to close horizontal distances. For the case where single tetroons were launched at the same site during

set intervals, the subsequent separation distances were a linear function of time. Comparisons of lateral standard deviations obtained by successive tetroon releases and randomized tetroon releases Angell and Pack (1965) showed that individual releases are only about 70% of the values derived from the sequential tetroon releases.

*Tetroon Grounding*

An important consideration for any tetroon flight is the possibility of grounding before the lighter than air gas used within the balloon envelope is used-up. Peterson (1966), had determined statistics for tetroon losses in his study. Most of the cases were though to be related to downward forcing motion. However, it was thought that about one-third of the cases were related to rainfall grounding. For the most part, it was found that tetroons maintained a near constant level as diurnal temperature changes which tends to lower to isopycnic surfaces during the day, is balanced by radiational heating.

A model was developed by Hoecker (1981a) to determine probable height variation during tetroon flight time. Unfortunately, it was determined that height variations in low level flights (~300 m), could exceed actual flight levels for a diurnal temperature variation of 13° C. The scenario when tetroons are at greatest danger due to grounding occur at low levels (i.e. < 200 m) in the early morning hours. Hoecker (1981a) determined that tetroons released at the minimum temperature for the day showed much lower float elevation as compared to tetroons released at the maximum temperature for the day. It should be noted though that radiational heating of the balloon itself was not included in the model.

Hoecker (1981b) noted that on many occasions grounded tetroons made of lear Mylar® have been found covered with frost. This would indicate that tetroons can cool below ambient air temperature, and Morel, et al. (1968) noted that upper troposphere balloons were being frosted when traveling through dense cirrus clouds with supercooled droplets. However, Morel, et al. (1968) did not encounter nighttime frosting as Hoecker (1981b) did. Lally (1968) suggested though that a metal cap could be used to mitigate frosting on 300 mb balloons.

Although frosting is to be expected in a cold climate, the occurrence of dew can occur in the tropics on tetroons. An improvement from the EOLE experiment Morel and Bandeen (1973) where tetroons were flown at lower tropospheric levels by Cadet, et al. (1975). Before tetroons were metalized on the upper hemisphere of the balloon, nighttime readings showed a temperature difference of 6°C. Subsequently, dew tended to form on these tetroons and shorten flight lifetimes. After metalized (vacuum-deposited aluminum) caps were utilized, temperature differences were brought down to daytime and nighttime differences of ± 2°C which consequently mitigated dew caused grounding.

Another important improvement made to tetroons by Cadet, et al. (1975) is the completely

enclosed design of the electronics package. If for some reason the tetroon is grounded in oceanic areas the system will be able to recover and hopefully float above the surface again. As will be shown later in this paper the smart balloon will utilize improvements suggested by Cadet, et al. (1975).

### *The Lagrangian Platform*

Atmospheric measurement is usually accomplished through traditional Eulerian measurement schemes such as radiosondes, stationary anemometers, of which make an instantaneous snapshot of the atmosphere. Even moving systems such as radiosondes and aircraft sensor measurements take an instantaneous measurement of the atmosphere that is mapped to a single physical location. Unfortunately, none of these methods can follow the evolution of a discrete air mass or process.

Temporal changes of an air mass cannot be ascertained with Eulerian methods unless a very dense network of measurement stations is used. Kahl and Samson (1986), found that even the National Weather Service (NWS) radiosonde regional network data were insufficient for use in deriving air mass trajectories, although high density meteorological networks though have been used to solve mesoscale and climatological problems. Unfortunately, the cost is prohibitive if operational forecasting is required over a large spatial scale.

Satellites use was attempted to makeup for the shortcomings of Eulerian methods as large, individual air masses (i.e.. clouds) are followed through their lifetimes. However, remote sensing methods cannot measure many key parameters such as vertical velocities and most importantly, fluxes. Small-scale problems cannot be solved because the resolution of satellites is also very low.

Because the Lagrangian frame of reference assumes a mean wind of approximately zero, the lateral flow in and out of Lagrangian volume is much less than a Eulerian volume. For a short time scale the Lagrangian volume may be considered completely isolated which allows for an "air parcel" approach.

In an atmospheric Lagrangian measurement, a parcel is tagged and is followed until the parcel is no longer of interest. At any point in time a parcel can be measured and the condition of the atmosphere is known. From a practical standpoint, spatial coverage is the limiting factor in Lagrangian measurements. Thousands of platforms would be required to adequately cover the globe for forecasting use; this is also a limiting factor for Eulerian measurements. Theoretically, tetroons should act as single particles for true Lagrangian motion, even though in practice the tetroon cannot be expected to do so.

The most beneficial aspect of Lagrangian measurement methods is the ability to measure fluxes. The ability to directly measure and corroborate what comes into and out of a box model

can only be determined from Lagrangian methods. In a Lagrangian measurement the size of the volume studied is small compared to the length of the trajectory. Therefore, for the species of interest, the data acquired is in a smaller volume compared to the trajectory length. Consequently, measurement resources are concentrated rather than dispersed, and long-range transport studies are easy to measure.

In many atmospheric models the flux in question is derived from the subtraction of two large numbers and the result is integrated over time. From a mathematical standpoint, this methodology is questionable. GCM $CO_2$ models for instance require small numeric flux values that are allowed to run for a long period of time. If for instance a key parameter such as air/sea $CO_2$ exchange is off by only a small fraction, the model will have very unrealistic results. Other models such as cloud feedback models that require flux values of dimethylsulfide (DMS) that are very small, can only be corroborated through Lagrangian methods.

Not only can Lagrangian methods determine flux values, but the flux at any point in time can be instantaneously determined. In Eulerian measurements, flux is determined by measuring the total change of a particular species of interest over a period of time. The total change in a species is divided by the total change in time, and a average flux over the period of time measured is derived. Typically, an average daily value is determined from these averaging methods which is deemed to represent the average changes over the day. However, what if the air mass and species of interest was only affected for a short period *in the day? Only a* Lagrangian measurement could determine if averaging really represents the physical processes going on.

Eulerian methods suffer from two inherent quantities that make this measurement method dubious for many atmospheric research topics. First of all, the area of interest has moved to a new locality, therefore the parcel method which much of meteorology theory is predicated on, is not possible. Secondly, for many measurements (e.g. the radiosonde network) the measurement interval is too coarse and many processes will be lost in the averaging methods utilized.

### *Verification*

An important consideration of Lagrangian measurements is the corroboration of traditional Eulerian measurements. Hay and Pasquill (1959) determined that Lagrangian and Eulerian velocities could be related by a simple decay coefficient $\beta$ . Where $\beta$ is defined as the ratio of the Lagrangian and Eulerian time scales over the integral time scale of the auto correlation function. Instrumented meteorological towers were used by Angell, et al. (1971), Pasquill (1974), and Hanna (1981) to determine this coefficient. It was found that $\beta$ constantly had a value of approximately four. Therefore, tetroons can be utilized to confirm more traditional

Eulerian methods.

It should be noted that actual tetroon motion and theoretical tetroon motion are not necessarily the same. With the advent of computers which model complex phenomena, the ability to empirically confirm models is paramount. Computer programming for complex phenomena (i.e. air pollution, cloud development, etc.) requires temporal information. Time evolvement is the fundamental strength of Lagrangian measurement which corroborates computer models (Hoecker, 1981b).

## 5 Tetroons for ASTEX/MAGE

The Atlantic Stratocumulus Transition Experiment / Marine Aerosol Gas Exchange (ASTEX/MAGE) was performed in June 1992 in the Atlantic near the Azores, was devised to measure the change in the sulfur budget. The species of interest was dimethylsulfide (DMS) which is thought to be an ocean derived gas that could brighten stratocumulus clouds, and subsequently could substantially change global albedo values.

Although aircraft, ground stations, and ships were important atmospheric constituent collectors, they were all Eulerian data collectors by nature. Therefore, the tetroon was relegated as the only Lagrangian method utilized that could determine MBL evolution. Another crucial aspect of tetroons is the ability to formulate trajectory analysis from the tetroon data collected.

Previous experimental attempts to understand oceanic clouds came from Duda, et al. (1991) during the First ISCCP Regional Experiment (FIRE) Marine Stratocumulus Experiment where tethered balloons to ~ 900 hPa were utilized. Although significant results were obtained and aircraft and models were used to corroborate results, this experiment was still a Eulerian based experiment that had inherent shortcomings. Therefore, a Lagrangian measure system is desired so that gaps in the understanding of oceanic cloud evolution can be resolved.

### *ASTEX/MAGE Results*

The ASTEX/MAGE tetroon system was composed of 1) a single Mylar® balloon envelope, 2) temperature/humidity sensors, 3) GPS receiver, 4) communications transceiver, 5) microprocessor and other associated D/A electronics and 6) power supply and battery pack.

For ASTEX/MAGE, the tetroon used the Global Positioning System (GPS) to determine its absolute position which then was relayed to an NCAR Electra, UK C130, or UW C131A.

Results from the ASTEX /MAGE Bretherton and Siems (1994) show that Lagrangian measurements from tetroons can simplify atmospheric measurements. Specifically, if horizontal advection can be removed, then various budgets (i.e. temperature, moisture, chemical, etc.) can be simplified. However, it should be noted that horizontal advection can be difficult to measure in areas of vertical wind shear.

## 6. Development of Smart Tetroons

The ability of an tetroon to relay information or to receive information from another device such as a satellite where information is disseminated is not new Blamont, et al. (1970), Morel and Desbois (1974), and Webster and Curtin (1974). The history of smart tetroons starts with several evolutionary developments.

The EPA Meteorology Branch at Research Triangle Pak had developed a Lagrangian marker that uses a standard FAA transponder and encoding altimeter and was flown during the 1980 Prolonged Elevated Pollution Episode (PEPE) experiment (Reisinger and Mueller, 1983). The Sandia National Laboratories group had developed a Lagrangian marker where a modulated audio radio signal is compared with a standard broadcasted audio signal. The subsequently measured phase shift can be used to compute the distance to the platform. This system allowed instrumented aircraft to fly very precise patterns relative to tetroon. In the last decade the NOAA ARLFRD group at Idaho Falls has developed a ranging system based on the (long-range (radio) navigation) LORAN navigation system.

Zak (1983) suggested the use of Lagrangian Measurement Platform (LAMP) which consisted of a tetroon system that could control its altitude. This system was to be based on the LORAN navigational system. Later, the Adjustable Buoyancy Lagrangian Marker (ABLM) was developed by Zak (1986) as a true isopycnic tracer, even under long-range transport conditions. This system is composed of a double CVB, with the inner balloon containing helium and the outer balloon containing ambient air, with a series of pumps and electrically controlled valves. The heart of the system is the microprocessor that monitors relative vertical air motion, pressure, temperature, wet bulb temperature, superpressure, and balloon skin strain which is subsequently relayed through the ARGOS system on TIROS satellites. The microprocessor can also be programmed to follow an isentropic algorithm and tell pumps and valves to add or subtract air to the outer balloon which causes a subsequent altitude shift. A fundamental problem with tetroon measurements are that flight heights are difficult to compute because superpressure, volume, density, and temperature of the tetroon; pressure, temperature, and density of the ambient air, are all simultaneously varying. With the advent of microprocessor technology the smart balloons can both relay these physical parameters, and make necessary inflight corrections if so desired.

Compared to the ASTEX/MAGE tetroon system, the smart tetroon will include the following additional features such as; 1) pressurized inner balloon and expandable outer balloon envelope, 2) cap surface on the outer balloon, 3) pressure pump, 4) ballast control valve, 5) press relief valve, and 6) pressure (strain) gauge on inner balloon.

An inherent advantage of the smart tetroon is not only the ability to record a very accurate

(ambiguity of tens of meters to centimeters) position, but to maintain that position. Traditional tetroons used superpressure of tens of millibars, depending on elevation and flight height, to maintain the tetroon at the desired isentropic level. This overpressure was used because of small leakage in the tetroon fabric, and to compensate for diurnal radiational heating which causes balloon "creep." However, the tetroon often seeks to establish a new equilibrium level due to atmospheric oscillations, strong vertical wind motions, and hysteresis problems establishing a new isentropic surface.

Angell (1964b) tried to estimate boundary layer kinematics and dynamics using tetroons. However, angular momentum estimates could only be approximated because vertical momentum fluxes could not be calculated due to the tendency for tetroons to follow and return to equilibrium floating levels. This compromise occurs because tetroons show hysteresis moving in upward and downward motion. Some of the hysteresis is due to balloon creep and a significant portion is due to tetroons establishing a new equilibrium level.

The smart tetroon allows algorithms within the electronics package to measure vertical motion and follow the motion caused by waves, fronts, etc., or to maintain the tetroon at a constant density or potential temperature surface. The tetroon could also be programmed to follow a particular species of interest to some degree, if small, light-weight sensors could be utilized.

During the 1994-1995 calendar year the smart tetroon will be developed and utilized during the Aerosol Characterization Experiment (ACE-1) planned for November-December 1995. Tetroons will compliment aircraft and ship measurements in a triangle between Tasmania, New Zealand, and Macquarie Island. The mission of the smart tetroons will be to characterize MBL aerosol evolution in a very remote atmosphere.

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